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HIGH FREQUENCY ROOM RESPONSES: acoustic design and the control of stereophonic image quality

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Summary

Aspects of mid and high frequency acoustic design are described, mainly in the context of relatively small rooms. The factors affecting the design and some of the difficulties which may be encountered are also discussed. The primary means of evaluating the quality of reproduced sound is the studio control room (and its associated equipment). This Report is written primarily in terms of the design of control rooms, but is directly applicable to other small spaces and, to a lesser extent, to larger spaces.

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HIGH FREQUENCY ROOM RESPONSES: acoustic design and the control of stereophonic image quality

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1. INTRODUCTION

This Report deals with those aspects of room acoustic design that relate to the physical behaviour and human perception of sound energy at mid and high frequencies in relatively small rooms. The accompanying aspects of low-frequency sound have been dealt with in companion publications[1,2].

Amongst the types of rooms for which acoustic factors are especially significant, are broadcasting and recording studios and their control rooms (cubicles). Listening rooms and other relatively small technical areas, for example, post-production suites, are also acoustically sensitive areas.

The studio control room is the principal point where the quality of broadcast or recorded sound is evaluated. However, it is the one part of the programme chain which is most difficult to design and regulate. The magnitudes of the defects introduced by the loudspeakers and the room acoustics exceed the imperfections of the electronic equipment by large factors.

This report is written mainly in terms of sound control rooms but most of it is directly applicable to the other small areas. Some aspects are also applicable to large television studios.

Bigger rooms, such as large, live-performance studios, concert halls and other venues have their own sets of acoustic problems and are not generally subject to the same acoustic design criteria as small rooms. They are not the subject of this report.

2. ACOUSTICAL BACKGROUND

2.1 General

The behaviour of sound in an enclosure is, in general, complicated. The range of wavelengths involved in normal audible sound, the variety of sizes of objects within a room and the distance travelled by a sound wave, even in a short time, combine to make any attempt at analytical treatment unrealistic.

At low frequencies, the main factors are the size and shape of the room, the wavelengths being so great that the only significant object is the room itself. The implications of this and the way it can be treated analytically are to some extent discussed in references 1 and 2. The upper limit of the low frequency region depends on the size of the room, but is usually less than 200 Hz.

At higher frequencies, the sound field is characterised by objects and surfaces being either comparable with or larger than the wavelength. This results in specular or diffuse reflection of that proportion of the sound wave that is not absorbed. It is almost always so complicated that it can quite reasonably be treated statistically, at least in part, so that minor details of the field are not relevant. The lower limit of this region is usually about 500 Hz.

One aspect of the high frequency sound field relates to the behaviour of the sound energy during the first few milliseconds after it leaves the source, and the way that is interpreted by human listeners. That aspect is not statistical and is significantly more amenable to theoretical treatment than the complicated diffuse field which follows the initial time period. It is common, and, within some limitations, meaningful to consider the sound energy propagation to be similar to the geometric properties of light. The methodology is called 'ray tracing'.

The division between low and high frequency regions leaves a middle region with some characteristics of both. The acoustic design of this region is particularly difficult. The frequency is high enough for many objects to have a significant size but low enough for there to be significantly non-statistical effects. Its acoustic treatment has to be a mixture of both the low and the high frequency elements, depending on which aspect of the sound field is under consideration, plus a large degree of experience.

2.2 Acoustic design for high frequencies

Acoustic design in the high frequency region falls naturally into two distinct time zones because of the way human beings perceive sound. The subjective response can be divided into two different time zones - the interval up to about 50-80 ms after the arrival at the listener of the sound following the most direct path from the source, and all of the the sound which arrives later than that.

The detailed structure of the earliest reflected sound, in time, level and frequency, gives auditory clues about the direction and distance of a sound source. This applies up to about the first 20 ms. Thereafter, between

about 20 and 80 ms, the main auditory cues are of the nearby environment — for example, the size of the room.

After the initial time interval the sensation of reverberance and the blending of the sound into a whole become the dominant factors.

2.2.1 Long-term effects

The two processes of absorption and reflection (either specular or diffuse) dominate the later part of the acoustic time scale, that is, after about 50-80 ms. In reasonably small rooms, the sound energy has, by that time, travelled a distance equal to several times the room dimensions and has been involved in a large number of interactions with the objects in the room. Generally, the sound field by that time is fully diffuse* or, at least, as diffuse as it will ever become.

All objects and materials absorb some fraction of the incident sound, converting the acoustic energy to heat in different ways. Some materials absorb so little that they may generally be neglected, but most are acoustically significant - even those that have no intended acoustic effect.

The human perception of this later sound is of an integrated whole, gradually decaying in level as the sound field energy is absorbed. This gradual, regular decay was one of the first aspects of perceived sound to receive formal study. There is some evidence that the ancient Greeks understood the concept and introduced means of controlling it in their theatres. Vitruvius[3], writing about the use of resonators in the Greco-Roman theatre in AD 160, said:-

"... By the adoption of this plan, the voice which issues from the scena, expanding as from a centre and striking against the cavity of each vase, will sound with increased clearness and harmony from its unison with one or the other of them".

The objective in those virtually anechoic open-air theatres was probably to increase the resonance, and thereby the substance of the voice, rather than to absorb the sound, but the concepts are clearly evident.

In more modern times, measurements have been made to derive descriptions more numerical than philosophical. This began with Sabine at Harvard[4] in the later part of the 19th century. When asked about the poor acoustics of his University's large hall, he made measurements of the time taken for a sound to decay by a given amount under different conditions. He used the sources of test signals that were readily available to him - organ pipes, whistles, horns, etc. and a stopwatch. The range of sound levels over which these measurements could be made lay between the loudest source and the local ambient noise - a range of about 60 decibels. Thus, his measure of decay time, and one which is still in use today, is the 'reverberation time' - the time taken for a sound to diminish to a level 60 dB below the initial level. He formulated the now familiar inverse objective relationship between the reverberation time and the total quantity of acoustic absorption present.

The reverberation time is a statistical description of the general properties of the acoustic field inside a large enclosure. It is unrelated to any of the fine detail of the sound field. It is also, by definition, an average property, both of the whole space and over the whole time interval. It can only be measured by taking the average of the individual results for a large number of positions and gives no information about the form of the decay. Despite these limitations, it has an important acoustical significance, even in every-day life. It approximates to what musicians call 'resonance' and is also closely connected with the musician's 'warmth'. It is the only numerical description of a room's acoustics about which there is almost complete consensus, yet it plainly does not give a full description, otherwise a small bathroom and a large television studio would sound the same — they might easily have the same reverberation time. Having the appropriate reverberation time could be described as a necessary but not sufficient condition for 'good' acoustics.

In practice, the reverberation time as scientifically defined is rarely used. The number of positions used for the measurement is almost always less than the statistically sufficient number, especially at low frequencies. Indeed, the 'reverberation time' at one position may sometimes be discussed. Equally commonly, the measurement is not made over the defined 60 dB range of levels. What is more frequently measured is the time taken for the sound to fall over some other range and the results expressed as though that rate of decay applied throughout. Sometimes, this is usually more useful because it can reveal significant departures from a uniform decay rate and thereby provide an additional degree of specification or analysis.

Because it is a generalised measure, independent of the detailed sound energy pattern in the room, its statistical relationship to the other generalised properties of the room can be quantified. The link

* A diffuse field is defined as one in which the statistical energy density is uniform throughout the space. It is a theoretical ideal which can, in practice, neither be verified nor (probably) achieved. However, it is a useful concept and many diffuse spaces approach the ideal to an adequate degree. Seriously non-diffuse spaces and their associated problems are much easier to identify.

between the size of the room, its contents and the reverberation time was originally expressed by Sabine as :

$$T = kV/S\,\alpha \qquad (1)$$

where T is the reverberation time in seconds, V is the volume, S is the total surface area of the room and α is the average absorption coefficient of the surfaces. For metric units, $k = 0.161$.

This expression can be derived theoretically and is reasonably valid for rooms with small amounts of absorption ($\leq \alpha\, 0.1$). For rooms with larger amounts, like most studios and control rooms, the more general expression, first derived by Eyring and Norris[5], is

$$T = -kV/S\log(1\text{-}\alpha) \qquad (2)$$

In all but the smallest rooms, the average surface absorption coefficient must have a component representing the absorption of the air itself added to it. This is usually insignificant at low frequencies but can become dominant at higher frequencies.

One of the most serious difficulties of acoustic design in this frequency and time region is the correct identification of all of the materials within a room. It is commonly believed (by non-acousticians) that only materials which are included for acoustic reasons have any acoustic effect. This is not true.

Acoustic defects which can arise in this later-time region (apart from simple errors in the achieved reverberation time) are mainly related to serious departures from a diffuse space. For example, two relatively highly reflecting surfaces facing each other may confine sound energy to a repetitive double-reflection process between them. This process will have a lower decay rate than the rest of the room so that, eventually, this comes to dominate the sound field within the room. The decay rate would then usually be two-valued, with a higher initial rate, followed by a lower rate later in the decay. This is generally unsatisfactory, and is subjectively described as a 'flutter echo' for a relatively slow repetition of high frequencies (>2 kHz). If the frequency band affected is somewhat lower (perhaps 500-800 Hz), and the repetition rate rather higher, it is termed a 'honk'. Double decays may also occur in situations with two or more interconnected spaces with widely different mean absorption coefficients, or as a result of objects acting as resonators.

2.2.2 Early effects

In the time immediately following the emission of a sound wave from a small source, the wave will propagate as if it were in an open space. Each radial vector from the point of emission can be treated somewhat like a light-ray. An entire branch of acoustics has been developed to study such ray-like propagation. At its simplest, each elemental ray may be followed through its interactions with surfaces and objects as they are encountered. Some of these methodologies follow the hypothetical sound rays until they vanish into insignificance.

In reality, the accuracy of representation of the interactions becomes inadequate for such extended recursion and the system becomes more or less chaotic. (Some ray-tracing implementations approximate the later behaviour by assuming non-geometric reflection for higher reflection orders[6].) However, the representation may be sufficiently realistic to be useful for the short term response and for a few interactions.

The human hearing response in the time domain has been widely studied. The 'early' sound can be subdivided into three different time-zones*. In the time period up to about 5 ms, there is no directional discrimination between the sound travelling along the direct path from source to listener and any reflected sound, provided that their relative levels are reasonable[7]. This 'precedence (Haas) effect' dictates that the apparent direction of the sound is not affected by reflected sound in the first 5 ms.

After this first time interval, and up to about 50-80 milliseconds after the arrival of the direct sound, the human auditory process can perceive and interpret a complex pattern of reflection arrival times. Parameters such as apparent source direction and distance are derived from the sound signal. In the time-zone between 5 and about 10-20 ms, reflections are capable of causing confusion about the apparent direction of a sound source.

After about 50-80 ms, at most, the sound energy is integrated so that reflection events are either not perceived individually or appear as discrete echoes, depending on their level relative to the remainder of the sound.

* Some of these figures for time limits are subject to significant discussions and continuing re-appraisal amongst acousticians. The values given here are intended to be illustrative and representative of the broad consensus of opinion. Their exact values are not relevant to the work described in this Report.

The perception mechanism is capable of carrying out all of these processes on a continuous pattern of arrivals - it does not need isolated sound events.

For the acoustic designer of sound control rooms, these figures mean that some control of the pattern of reflections reaching the listener is desirable.

An effect of very early reflections, within the period up to about 3-4 ms, is perceived more in the frequency domain than in the time domain. The direct and the reflected sound will create an interference pattern, with partial cancellation at frequencies where the path-length difference is an odd number of half wavelengths. At even multiples, the interference will be additive. The result will be an effective frequency response with a regular pattern of peaks and dips.

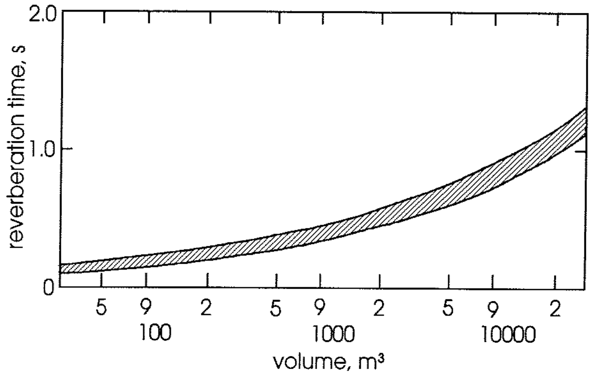

Fig. 2 - Recommended reverberation times for television studios

3. HIGH FREQUENCY ACOUSTICAL DESIGN IN DETAIL

3.1 The diffuse field - reverberation

Methods of controlling the later part of the sound field are well established. The field is assumed to be reasonably diffuse so that the general principles of average absorption coefficients and statistical absorption processes can be applied. At least in the smaller rooms, the only meaningful objective measure of the sound field is the reverberation time[8]. Targets for mean reverberation time in different sizes and types of areas have been specified for many years, based on experience and common usage. Figs. 1 and 2 show the recommended ranges of reverberation time from reference 9 . The usual objective is to design for a reverberation time which is independent of frequency (except perhaps at low frequencies and, sometimes, in large music studios).

The design calculations are generally based on Equation 2 and standard lists of material absorption coefficients, together with the room dimensions.

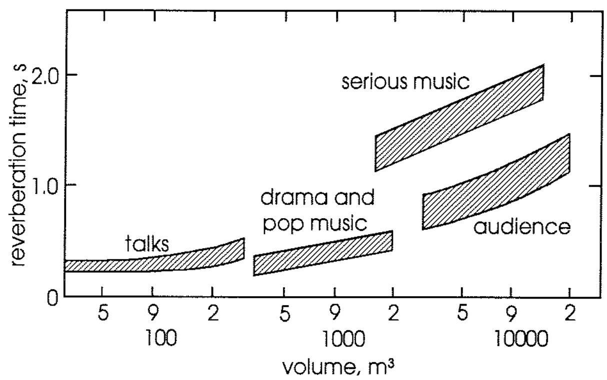

Fig. 1 - Recommended reverberation times for sound studios

However, a number of errors can arise during this process, usually resulting in failures to meet the design reverberation time specification. They can be classified under four general headings:-

a) Material acoustic properties not known at all.

Even in an otherwise acoustically-designed room many materials have unspecified acoustic properties. In most cases, it is impractical to measure the acoustic properties of every component. For some elements, for example the walls, ceiling and floor, it is essentially impossible (because they may not exist until the room is constructed). In many cases, the acoustic designer may be unaware of the intentions of other members of the design team in respect of items which are 'non-acoustic'. Estimates can be made, but some errors are inevitable.

b) Material acoustic properties measured under different conditions.

The acoustical properties of materials are usually measured in a different environment or under different conditions to those which will apply in practice. Standardised measurements (ISO, BS, ANSI, etc.) are carried out in large, nearly empty rooms with as little other absorption present as possible. The resulting relatively long reverberation time, together with the deliberate steps taken, through the use of diffusing elements, ensures that a highly diffuse sound field exists. In addition, the relative freedom from adjacent absorbing materials allows a significant degree of diffraction at the edges of the test sample. These factors tend to produce higher absorption coefficients than occur under practical conditions.

c) Interaction of material acoustic properties.

A feature of rooms with relatively large quantities of acoustic treatment is that the apparent effectiveness of some of the treatment is reduced by the presence of the remainder. To some extent, this factor is the opposite of that in 'b' above. In principle, this effect should lead to more uniform reverberation time characteristics as saturation is approached at the frequencies most heavily treated.

An investigation has been carried out into these interactions[10]. Effective absorption coefficients measured by removing samples from an otherwise heavily treated room (typical of a contemporary sound control room) showed values very different from those measured in the conventional way. In some cases, material with a high absorption coefficient, as measured under standard test conditions, appeared to have a negative absorption in the treated room. This mostly served to illustrate how far such rooms depart from an ideal diffuse sound field.

d) Unavoidable materials.

In many cases, other design criteria will demand the inclusion of materials with acoustical properties known to be detrimental or difficult to integrate into the acoustic design. Examples are: decorative stretched fabric wall finishes, carpet tile floor coverings (especially in association with acoustic tile ceilings), windows, doors and equipment bays in acoustically difficult locations .

These uncertainties can only be overcome by relying on previous experience with similarly-treated rooms.

3.2 The duffuse field - diffusion and resonances

In addition to failures to meet an objective reverberation time specification, other acoustical defects can arise in the later time period.

Diffusion is one of the unquantifiable aspects of a room design. Theoretically, it is a measure of the uniformity of the reverberant sound field. However, a numerical value would have little subjective significance and there is no practicable method of 'designing' a room to a given level of diffusion. The acoustic design should usually ensure that the sound field is as diffuse as possible. In the past, it was common to provide simple geometric irregularities, such as part-cylindrical or angular prismatic columns, on otherwise flat surfaces. This is not now regarded as satisfactory, because of the ineffectiveness of even quite large structures and because the regular (or near-regular) spacing of such elements introduced audible acoustic anomalies into the reflected sound field. Recently-developed, pseudo-irregular diffusing structures[11,12,13] do not suffer from the regular spacing effects and have some role to play in augmenting the diffusion. However, the most practical and efficient means of providing diffusion is through the use of different types of acoustic treatment intermixed in relatively small patches[14,15]. This causes distortion of the reflected wavefronts by diffraction, mainly at the edges of the patches.

The diffusion will inevitably be less in more heavily treated rooms because of the shorter mean free path in relation to the room dimensions; consequently, there will be a smaller number of interactions between sound wave and room surfaces.

Acoustic anomalies, such as colorations, resonances and 'flutter echoes' are clearly to be avoided. One family of such defects occurs because of vibrating structures and equipment. These are easy to avoid in principle but can often be overlooked during the design. Technical equipment cabinets, waste bins, light fittings, gas-filled fire extinguishers and many other objects form mechanical systems with medium or low values of damping. They will cause audible colorations in the later part of the sound decay process. For inaudibility, it is sufficient to increase their damping factor until the decay rate is similar to or greater than the room decay rate; they may act as significant resonant absorbers if the decay rates are similar and the areas large.

A second class of resonances occurs acoustically, as a vibrating system consisting primarily of the mass and compliance of the air. An enclosure with a small aperture will behave as a Helmholtz resonator, the mass of the air in the aperture resonating with the compliance of the air in the enclosed space. Depending on the acoustical 'size' and the damping factor, it might cause either excess absorption or coloration of the later part of the decay. Helmholtz resonators are widely used as intentional low-fequency absorbers, offering high absorption in a relatively small space. As accidental absorbers, they can occur as parts of equipment or furniture or ventilation systems.

The third important class of acoustic resonances is that caused by transit-time effects. For example, sound energy travelling between two opposing reflecting parallel surfaces, in a direction normal to the surfaces, will be repeatedly reflected between them. This causes a characteristic rapid fluctuation in sound, usually with a non-uniform (coloured) spectrum,

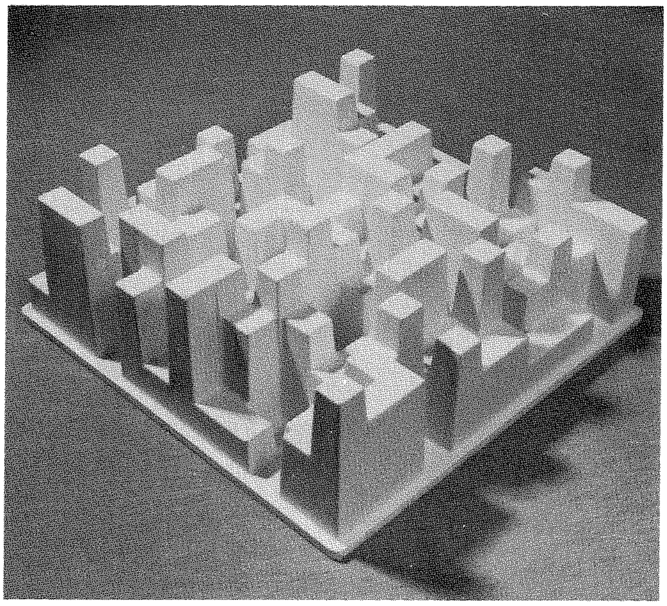

Fig. 3 - Quadratic residue diffuser

because the absorption characteristics of the surfaces are emphasised by the repeated reflections.

A common example of this effect is the reflection between floor and ceiling in a typical control room. Usually, neither of these surfaces has much low-frequency absorption. They are, however, usually too small to reflect low-frequency sound in a specular way. Both usually have significant absorption at high frequencies. This leaves the mid-frequency range (500 Hz to 1 kHz) to create repeated reflections, resulting in a highly-coloured late decay. The effect is more noticeable in rooms with large quantities of acoustic treatment on the the walls, giving an even greater discrepancy between decay rates in the different directions. The sound field eventually becomes dominated by the energy 'trapped' by repeated reflections between floor and ceiling. Onomatopoeically, it is usually described as a 'honk'. Fig. 3 shows the pseudo-random diffuser described in reference 13, which was specifically designed to reduce this problem, installed in a Music Studio Annexe. It is very effective, even at a relatively small installation density (about 20% coverage).

A similar problem can occur at high frequencies if two surfaces which reflect high frequency sound are placed in opposition. Then, the repeated reflection causes a 'flutter' echo, in which the high frequency components from transients in the sound are repeated at an audible rate. Because these reflections usually involve very high frequencies, the effect can be caused by quite small reflecting surfaces, of the order of 0.2 m^2. It can be avoided either by slightly angling some or all of the surfaces or by covering them in acoustic absorption which is effective at frequencies above about 2 kHz.

In very rare cases, three or more such surfaces (arranged as a polygon) can form a physically more complex but acoustically identical effect. It should also be remembered that low-frequency absorbers are, by definition, high-frequency reflectors.

3.3 Early reflections - controlling the images

The control of early reflections and their effects on stereophonic imaging applies mainly to those rooms in which sound is reproduced by loudspeakers. These include sound control rooms, post-processing areas and listening rooms. It is especially important in rooms for two-channel or multi-channel stereophony.

The extent to which control of the early reflected energy is necessary is not clear. Much work has been done by many workers to assess the audibility of echoes and reflections[16]. Most of this is applicable to large performance spaces and much of it relates to the audibility of single echoes. In contrast, the problem of the effects of a multiplicity of early reflections on stereophony is less well reported. This is inevitable. A large number of dimensions are involved in such investigations; time and direction of arrival, relative amplitude and relative frequency response are all important parameters. When multiplied by even a small number of reflections, the investigation problem becomes intractable. It is quite clear that the threshold of audibility of a single early reflection, which some results suggest is at a level of about –30 dB (or even –40 dB) relative to the direct sound, is not an appropriate criterion for the perception of stereophony in real rooms. Early reflection levels in conventional sound control rooms are in the range –3 dB to –12 dB for the first 20 ms and stereophonic listening has been carried out reasonably satisfactorily for many years in such rooms. Some recently-reported work[17] suggests that a target of –10 dB and 15 ms would be appropriate for the perception of stereophony unimpaired by changes to the timbre of the sound. That is, at the listening position, no reflection greater than –10 dB relative to the direct sound would occur in the first 15 ms. That work, however, was not related to the perception of direction.

In other fields, time windows of up to 80-100 ms are used to calculate some quality criteria[16,18,19]. These are, however, not related directly to the perception of multi-channel stereophony as commonly implemented in small rooms. Indeed, it is well-known that the

common form of two-channel stereophony, using a pair of spaced sound sources, works less well or not at all if the spacing of the two sources is larger than about 4-5 m.

To control the early sound energy, those surfaces located in positions capable of creating early reflections at the listening position must be designed to avoid causing such reflections. Possible methods include absorption, diffusion at the point of reflection, or redirecting the reflected energy away from the listener[20,21].

Absorption has been used extensively since the earliest days of two-channel stereophony. It can lead to excessive acoustic treatment and oppressive working environments if the majority of potential reflections are controlled.

Acoustic diffusion could be used to avoid the need for excessive absorption. The kind of pseudo-random acoustic diffusers commercially available, and those described in reference 13, are effective in scattering the reflected sound energy over a wide angle. However, the use of such devices over large parts of the internal room surfaces greatly increases the area of potential reflector, albeit with a wide spread of arrival times.

An alternative approach, Controlled Image Design (CID), which uses direct reflection rather than absorption or scattering, is described in references 22, 23, 24. For that work, a target of –20 dB for 20 ms was initially adopted for the development of an acoustic design with controlled early reflections. This target was ultimately shown to be barely achievable (for all frequencies above 1 kHz) in a real room, even taking stringent measures to control reflections. The more practical target of 15 dB for 15 ms probably represents a design target which gives adequate reflection control.

Very early reflections, within about 1 ms, can occur from the top surface of the mixing desk (control console). If the reflected energy level is greater than about –10 dB relative to the direct sound, the peak-to-peak variation for the combination of direct and reflected sound will be greater than 5 dB and will probably be objectionable. It is likely that a direct desktop reflection would have a relative level of about –2 dB, set almost entirely by the additional pathlength difference (the desktop surface being a nearly perfect reflector of high frequencies). This would create a frequency response pattern with a peak-to-peak variation of nearly 20 dB and would be most undesirable.

4. SOUND ABSORPTION

4.1 Acoustic treatment

In the design of a room it is very rare to find that the basic structure and furniture provides just the right degree of control of the internal acoustics. The introduction into a room of materials whose sole or main purpose is the efficient absorption of airborne sound energy (acoustic treatment) is the principal means of control. Thus, the study of sound absorption is fundamental. Essentially, some fraction of the total sound energy is converted into heat energy when sound waves traverse any transition between two media. In general, the two media will both have characteristic acoustic impedances, each with real and reactive components.

The ratio of the energy absorbed, to the maximum which could be absorbed by a perfectly matched load, is given by:

$$\alpha = 4 R_2 2 / ((R_1 + R_2)^2 + (X_1 + X_2)^2) \qquad (3)$$

where R_1 and R_2 are the real parts of the impedances of medium 1 and medium 2 respectively and X_1 and X_2 are the reactive parts.

In many cases of sound absorption, the first medium will be air and the wavefront will be essentially plane. This makes the impedance of the first medium real and of magnitude about 410 acoustic units (rayls). This value is derived from the product of the density of air, ρ_0 (taken as 1.18 kg/m^3), and the wave velocity, c (assumed to be 340 m/s). It is usually denoted by $\rho_0 c$.

Thus, the conditions for high values of sound absorption are that the reactive impedance of the absorbing material should be small and the real part should be roughly equal to $\rho_0 c$. The absorption coefficient would then be close to unity.

The main principle employed for high-frequency acoustic absorption is the use of a dense mass of fibrous material with many open pores, typically glass wool or mineral wool. This material behaves in a manner characteristic of a high-loss transmission line. Sound energy which enters the pores of the material is quickly dissipated as heat by the viscous friction which results from the relative motion of the air molecules and the material fibres. Provided that the material thickness is great, practically all of the sound energy entering the material will be absorbed before reaching the far side. Thus, the material absorbs a large proportion of the incident sound; that is, it has a high absorption coefficient. The main problem with such an absorber is the reflection from the front surface; by definition, the

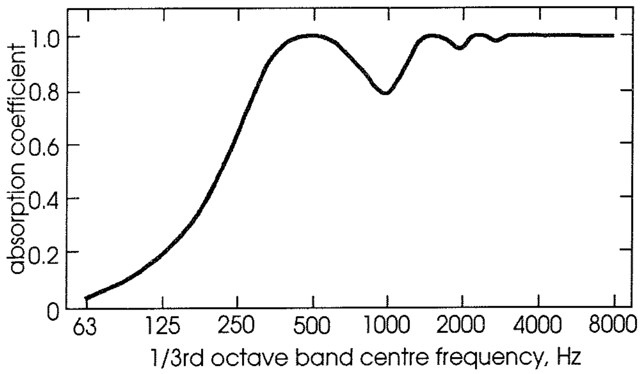

Fig. 4 - Theoretical absorption coefficient for spaced absorber (airspace depth = 200 mm)

interface cannot have the same characteristic impedance as the air. For the most demanding applications, such as laboratory measurement rooms, the material is made in the form of tapered wedges, to provide a gradual transition from the air to the material.

For thinner sections of the same kind of material, the sound energy will still have a significant magnitude when it arrives at the rear surface. If the backing is solid this remaining energy will be reflected and will re-emerge after another transit through the material. For materials which are thin compared with the wavelength of the incident sound, the relative velocity between the air molecules and the material will be small because of the pressure maximum (and velocity minimum) near to the hard surface. Consequently, the acoustic loss will also be small. The absorption coefficient increases with material thickness until it is a max mum at about $\frac{1}{4}$-wavelength. Depending on the the loss factor of the material, the absorption may fall somewhat at about $\frac{1}{2}$-wavelength and thereafter show a diminishing cyclic characteristic with increases in thickness (or frequency). Fig. 4 illustrates an idealised version of such behaviour.

Some saving can be made from the fact that the parts of the material nearer to the hard surface are proportionally less effective and can be omitted without much detriment to the overall acoustic performance. An absorber consisting of, say, 50 mm of mineral wool over a 0.25 m airspace would be acoustically nearly as effective as the full thickness of mineral wool.

Acoustic treatment of all types is often provided in the form of 'boxes' of about 600 mm square[25]. This modular construction allows the architectural design to proceed without requiring the details of the acoustic treatment and, if necessary, permits easy changing of the treatment for final tuning. In principle, it also allows for the acoustic treatment to be removed and reused. Because it is modular and usually constructed in a factory by a specialist manufacturer, away from the building site, it is also relatively cheap and reliable.

However, for large television studios, with the large amount of treatment required to produce short reverberation times, the modular approach would need a very large number of boxes. It is generally more economical to provide that amount of material as part of the main contract, at the time of construction.

4.2 Incidental absorption

All materials within a room have some effect on the sound field. Some of these effects will be so small as to be negligible, except sometimes in very large spaces or rooms, such as reverberation chambers, where the intention is to minimise the absorption. The acoustic designer is advised to check the significance, as far as possible, of every single element, beginning with the exterior shell of the room.

High frequency 'accidental' absorption may result from carpets and ceiling tiles (both of which are relatively obvious and often included directly in the acoustic design), curtains and seating (the latter being of the greatest importance in large auditoria[26]). The contemporary preference for fabric finishes to wall surfaces is virtually impossible to include in an acoustic design (if a uniform reverberation time characteristic is required). The stretched fabric over the inevitable airspace behaves in just the same way as any other spaced acoustic absorber. It is difficult to achieve an airspace much less than about 10 mm in practice, giving a peak of acoustic absorption at about 8 kHz. Even with the lightest fabric which will be optically satisfactory, the peak value of absorption coefficient is likely to be about 0.3. It is usually impossible to compensate for this in the other acoustic treatment, especially as the wall surfaces form such a large fraction of the total. Almost inevitably, areas so finished will show a severely diminishing reverberation time above about 4 kHz.

Table 1 (shown in the Appendix) gives typical values for a selection of studio and control room materials. Most of the values are from measurements made in standard measurement facilities. A small number have been derived from measurements in studios or control rooms. The values in the table are for octave frequency bands only. In practice, because low frequency absorp-absorption is usually narrow-band, it is necessary to use closer spacing of the frequency intervals for the lowest frequencies.

5. DESIGN EXAMPLES

5.1 Reverberation time

The calculation of the theoretical reverberation time in an enclosure, based on Equations 1 or 2 above, is a straighforward numerical process. It may conveniently be carried out by a standard 'spreadsheet' application on a personal computer. Table 2 (shown in Appendix 3) shows a reproduction of the output from a spreadsheet-based calculation for a typical small studio. (Of course, the spreadsheet also includes database look-up functions and calculation areas for the summation of the products of area and absorption coefficients.)

The database used in this case included the effects of air absorption. The calculation also included means for incorporating an 'empty' reverberation time characteristic. This could take any values from very large numbers representing a theoretically empty room to an almost complete room for which only minor adjustments were required.

In practice, because of the variable factors described above, it is very likely that a room constructed and acoustically treated according to this theoretical design process would not measure out exactly as calculated. Previous experience with similar rooms or, alternatively, on-site evaluation and adjustment during the progress of the construction, may be used to achieve the desired result.

5.2 Distribution of acoustic treatment

In order to maximise the diffusion, the acoustic treatment must be distributed in relatively small patches, with the various types intermixed. However, it is also necessary to avoid having reflecting surfaces that are situated opposite each other, at least around source/listener/microphone heights. Low-frequency absorbers are by definition high frequency reflectors. This, and the inevitable quantity of doors, windows, equipment bays, light fittings, mixing desk and other necessary fittings, limit the degree to which intermixing can be achieved.

5.3 Early reflections

The design of early reflection control structures is described in full in reference 22. In principle, surfaces potentially capable of causing acoustic reflections which would reach the listener within about 15 ms of the arrival of the direct sound are angled to reflect the sound in a different direction.

In the three-dimensional space of a room, and for at least two sound sources (for stereophony), the problem is complex enough to require the use of a computer to generate guidelines for surface orientations. The solution may be found for just two dimensions (for example, plan and elevation), or it may include additional sections. In either case, it is important for aesthetic reasons to coordinate the surfaces in the various sections to align with each other.

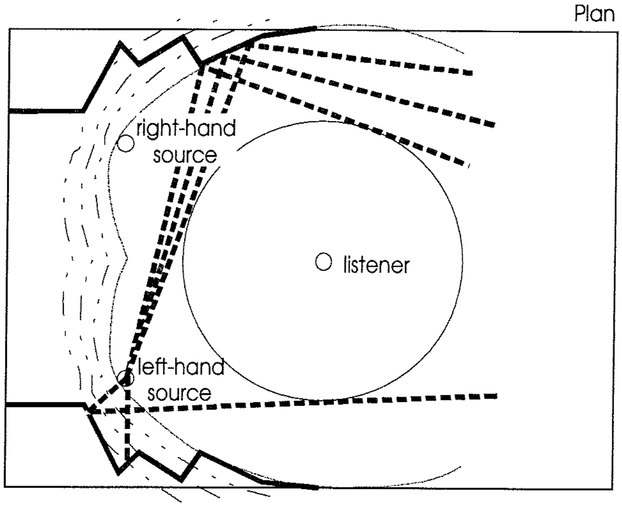

Fig. 5 - Example of Controlled Image Design

In small rooms, in order to achieve the necessary transition between, for example, the front and sidewall surfaces of the basic shell of the enclosure, it will be necessary to subdivide the angled surfaces. This creates steps between them, in the manner of a 'Fresnel' lens.

Fig. 5, taken from reference 22, illustrates the principles of a computer program which generates guidelines showing the limiting angles for reflecting surfaces at any point in the room. The principle is that no first-order reflection should pass within a circle around the main listening position. In the limit, the reflections are tangential to that circle. The resulting framework can then be imported into a CAD package for the development of the actual reflecting surfaces. In Fig. 5, the positions of the external shell and the source and listener positions are shown. The guideline framework has been edited to remove non-relevant lines and is shown as faint dotted lines. The reflecting surfaces are shown as bold lines — in the limit, just tangential to the guidelines. The steps between the reflecting surfaces are shown as total absorption.

6. CONCLUSIONS

This Report has presented an overview of some of the problems encountered in the interior design of acoustically sensitive areas. As such, little of the material is novel. Most can be found in text books on acoustic design and other publications. It was primarily intended

as a companion document to those previously published on the low-frequency acoustic problems of small rooms.

It also serves as an introduction and companion document to those Reports relating to the development of the Controlled Image Design principles for control rooms and the implementations of some examples of that principle.

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APPENDIX

Table and spreadsheet

Table 1
Typical acoustic absorption coefficients of common building and furnishing materials.

Octave frequency band centre, Hz	63	125	250	500	1 k	2 k	4 k
Material							
225 mm brickwork (structural)	0.05	0.05	0.04	0.02	0.01	0.00	0.00
113 mm brickwork (structural)	0.10	0.08	0.05	0.02	0.00	0.00	0.00
75 mm breeze block (structural)	0.09	0.13	0.16	0.03	0.00	0.00	0.00
Timber stud wall (structural)	0.27	0.24	0.12	0.06	0.02	0.00	0.00
Board on joist floor (structural)	0.10	0.10	0.07	0.01	0.00	0.00	0.00
12 mm wood panels on 25 mm battens	0.33	0.31	0.33	0.14	0.10	0.10	0.12
Glass (> 6 mm thick)	0.03	0.03	0.03	0.03	0.03	0.03	0.03
3 mm hardboard on 25 mm battens	0.30	0.32	0.43	0.12	0.07	0.07	0.11
Brick (surface)	0.02	0.02	0.02	0.03	0.04	0.05	0.07
Rough concrete (surface)	0.01	0.01	0.02	0.04	0.06	0.08	0.10
Smooth plaster, painted	0.01	0.01	0.01	0.02	0.02	0.02	0.02
Wood (surface)	0.05	0.06	0.07	0.09	0.10	0.10	0.12
Lino	0.02	0.02	0.02	0.03	0.03	0.04	0.04
Rubber flooring	0.01	0.02	0.03	0.04	0.04	0.02	0.02
Audience, units/person	0.15	0.33	0.40	0.44	0.45	0.45	0.45
Orchestra, units/person inc. instruments	0.20	0.40	0.85	1.15	1.39	1.30	1.20
Orchestral rostrum (per sq. m)	0.44	0.36	0.11	0.10	0.15	0.23	0.15
Haircord carpet on underfelt	0.05	0.13	0.17	0.24	0.29	0.30	0.30
Wilton carpet on underfelt	0.04	0.08	0.22	0.51	0.64	0.69	0.71
Typical carpet tiles	0.01	0.02	0.11	0.11	0.39	0.45	0.55
Curtains, drama, sailcloth, draped	0.03	0.03	0.04	0.10	0.17	0.18	0.15
Curtains, velour, draped	0.05	0.06	0.31	0.44	0.80	0.75	0.65
Lightweight fabric over 50 mm airspace	0.00	0.04	0.10	0.20	0.50	0.60	0.50
Fabric cover for lf absorbers	0.00	0.00	0.00	0.00	0.03	0.10	0.40
Ceiling tiles over 25 mm airspace	0.02	0.11	0.33	0.68	0.72	0.51	0.47
Ceiling tiles over 600 mm airspace	0.66	0.74	0.75	0.67	0.66	0.62	0.58
25 mm Min. wool, 5% perf hardboard cover	0.03	0.09	0.47	1.12	0.90	0.57	0.31
25 mm Min. wool, 25 mm airspace, 5% cover	0.04	0.14	0.65	1.18	0.90	0.57	0.31
25 mm Min. wool, 175 mm airspace, 5% cover	0.35	0.51	0.89	0.99	1.02	0.82	0.44
50 mm Min. wool, 5% perf. cover	0.10	0.31	1.10	1.20	0.90	0.57	0.31
50 mm Min. wool over 150 mm airspace	0.60	0.90	0.95	0.80	0.81	0.83	0.85
A1* Modular absorbers	0.46	1.11	1.27	1.23	1.20	1.18	1.15
A2* Modular absorbers	0.25	1.07	0.69	0.59	0.38	0.24	0.22
A3* Modular absorbers	0.40	0.88	0.94	1.12	1.00	1.00	0.91
A8* Modular absorbers	0.45	1.17	1.11	1.28	1.15	0.98	0.87
A9* Modular absorber	0.42	1.13	0.91	1.30	1.25	1.17	1.25
D2* measured in 106 cu.m.	1.25	0.81	0.87	0.43	0.30	0.20	0.13
D2* measured in 8151 cu.m.	1.13	1.23	1.18	0.62	0.40	0.20	0.03

* Proprietary modular absorbers, see Reference 9

Table 2
Room acoustic design spreadsheet.

Room data (m) -	**Length:**	8.1
	Width:	6.9
	Height:	3.7
Relative humidities (%) -	**old:**	50.0
	new:	50.0
	Volume:	206.8

Ref.	**Title**	**Area**
7	225 mm BRICKWORK (STRUCTURAL)	30.0
10	CAMDEN WALLING (STRUCTURAL)	30.0
11	BOARD ON JOIST FLOOR (STRUCTURAL)	55.9
21	SMOOTH PLASTER PAINTED	54.6
24	GLASS > 6 mm THICK	6.0
37	WILTON CARPET ON UNDERFELT	55.9
45	CURTAINS VELOUR DRAPED	6.0
49	Fabric over A2	32.4
50	Fabric over A3	28.8
75	A2[1]	32.4
77	A3[1]	28.8

Freq. Hz	**Old RT,s**	**New RT,s**
50		.80[2]
63		.80[2]
80		.68[2]
100		.36
125		.34
160		.35
200		.36
250		.38
315		.35
400		.32
500		.30
630		.30
800		.30
1 k		.31
1.25 k		.31
1.6 k		.31
2 k		.31
2.5 k		.30
3.15 k		.29
4 k		.29
5 k		.29
6.3 k		.29
8 k		.29
10 k		.29
Average		.30

Notes:

1. Proprietary modular absorbers, see Reference 9.

2. This incomplete example shows an excessive bass rise which would need additional treatment for most applications.